

Optimized biasing of pump laser diodes in a highly reliable metrology source for long-duration space missions

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ABSTRACT

Optical metrology system reliability during a prolonged space mission is often limited by the reliability of pump laser diodes. We developed a metrology laser pump module architecture that meets NASA SIM Lite instrument optical power and reliability requirements by combining the outputs of multiple single-mode pump diodes in a low-loss, high port count fiber coupler. We describe Monte-Carlo simulations used to calculate the reliability of the laser pump module and introduce a combined laser farm aging parameter that serves as a load-sharing optimization metric. Employing these tools, we select pump module architecture, operating conditions, biasing approach and perform parameter sensitivity studies to investigate the robustness of the obtained solution.

Keywords: 808nm diode pumps, beam combining, reliable optical pumps, NPRO lasers, optical metrology

1. INTRODUCTION

The SIM Lite instrument is an optical-wavelength Michelson stellar interferometer¹, that collects star light with two 50 cm-diameter telescopes (siderostats) separated by a 6 m baseline (Fig. 1). SIM Lite was developed to perform astrometry with micro-arcsecond precision, and its scientific goals include finding and cataloguing earth-like planets around nearby stars, mapping the distribution of dark matter in the Milky Way, as well as precision stellar astrophysics and supermassive black hole astrophysics.

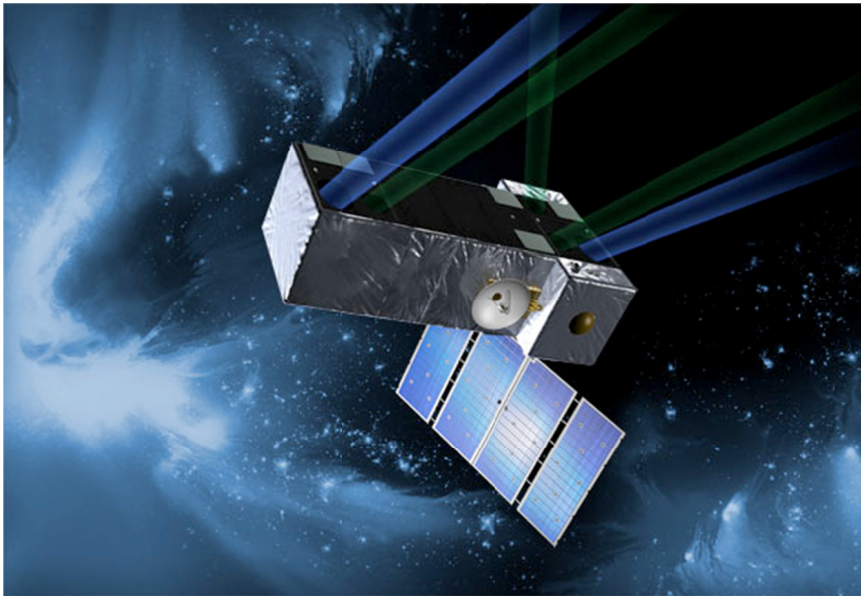


Fig. 1. Artistic rendering of SIM Lite spacecraft.

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Optical heterodyne metrology is key to achieving the SIM Lite performance requirements. The SIM Lite metrology source employs an Nd:YAG-based Non-Planar Ring Oscillator (NPRO) laser optically pumped by multiple 808 nm laser diodes. The reliability of the NPRO laser is limited by the reliability of the Laser Pump Module (LPM). This paper describes how the design of the laser pump module was selected and optimized to meet the SIM Lite mission reliability requirements.

The structure of the paper is as follows. In Section 2, we will provide a brief background on the optical metrology in the SIM Lite instrument and the reasons an NPRO laser was selected for the SIM Lite metrology source. We also discuss the performance and reliability requirements levied on the laser pump module. Section 3 describes how the LPM configuration was selected – starting with a brief review of laser diode reliability, followed by the description of Monte-Carlo simulations used to predict LPM reliability, and addressing various trade-offs that were considered in the process of choosing a preferred solution. We also introduce the combined laser farm aging parameter that we use for optimization of load-sharing among lasers. Section 4 shows the results of a numerical investigation performed on the selected laser pump module configuration to evaluate its sensitivity to changes of various key parameters, in order to ensure the robustness of the selected design. The results are summarized in Section 5.

2. SIM LITE METROLOGY LASER

2.1 SIM Lite Configuration and Need for Optical Metrology

A two-dimensional stellar interferometer configuration² is shown in Fig. 2. To measure the angle between the interferometer baseline and the target star, the following parameters must be tracked: (1) fringes formed by interfering starlight coming from the two siderostats, (2) relative optical path changes introduced by the delay line, and (3) drift of the baseline itself. Optical metrology is responsible for performing tasks (2) and (3) – while “internal” metrology monitors the delay line displacement, “external” metrology truss monitors the drift of the science interferometer baseline as well as its relationship to the guide interferometer baselines (two guide interferometers keep track of the instrument orientation in space with respect to bright “guide” stars).

SIM Lite employs heterodyne optical metrology, with one metrology source that consists of a laser and acousto-optic frequency shifters feeding all internal and external metrology channels (gauges) after the optical signals are split in a fiber distribution assembly.

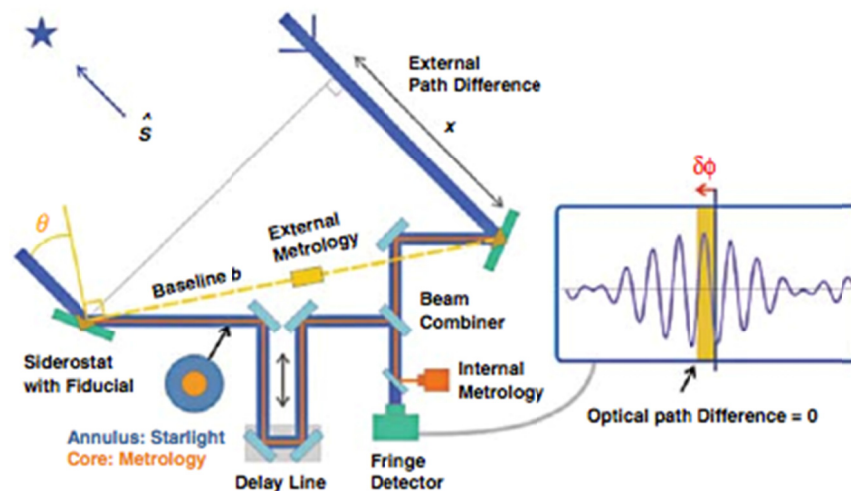


Fig. 2. Simplified two-dimensional representation showing key components of SIM Lite stellar interferometer².

2.2 SIM Lite Metrology Laser

The laser used for the SIM Lite metrology source needs to possess the following characteristics:

1. Narrow linewidth, since wavelength stability is a fundamental limitation on the precision of the metrology gauge.
2. Low intensity noise, since intensity noise can limit phase measurement accuracy after heterodyne detection.
3. High optical power sufficient to power all external and internal metrology gauges.

Nd:YAG-based Non-Planar Ring Oscillator (NPRO) lasers, first demonstrated in the 1980s³, are appealing for such applications. NPRO lasers produce hundreds of milliwatts of optical power at 1064 or 1319nm and are notable for their low intensity noise and intrinsically narrow linewidth, typically ~4KHz free running. In addition to these performance advantages, the compact NPRO cavity leads to an environmentally robust laser.

SIM Lite selected a 1319nm, 300mW NPRO as the optical source for the metrology system. One of the NPRO Laser Heads (LH) developed for this program is shown in Figure 3(a). Other space missions that have either flown or selected NPRO lasers for their optical metrology source include the Tropospheric Emission Spectrometer (TES) that used a 1064nm, low optical power NPRO to provide precise measurements of the path length difference between two arms of the Fourier transform spectrometer⁴, and the Laser Interferometer Space Antenna (LISA) which plans to use a 1064nm NPRO for inter-spacecraft laser ranging⁵.

The SIM Lite metrology laser must deliver 300mW of power over 5.5year mission life at 1319 nm with 99.7% probability of success. Optical pump reliability is a key constraint in the adoption of NPRO lasers for multiyear missions. The NPRO utilizes end pump configuration, which defines the lasing mode profile through a combination of gain and thermal profiles within the Nd-doped YAG. Figure 3(b) shows a reproduction of the absorption spectrum of 1% Nd:YAG⁶. While several absorption bands exist between 790 and 820nm, the band of interest for NPRO pumping extends from 805 to 809nm. Laser diodes in this wavelength region are fabricated from the GaAs/AlGaAs/InGaAsP family of materials. In this material family diode median life, T_m , at rated conditions has been reported in the range of 5,000^{7,8} to 100,000^{9,10} hrs (0.5 to 11 yrs). Note that, at the median life, the population reliability is 50%; that is after T_m elapsed hours half the diode population has failed. Assuming a median life of 100,000hrs and a mission life of 5.5yrs, the reliability of individual diodes at mission end is only 76%. This is insufficient to meet the aforementioned 99.7% reliability requirement. In light of this, NPRO pumping schemes must include spare laser diodes and an optical combiner to deliver the necessary pump power to the NPRO over the mission life.

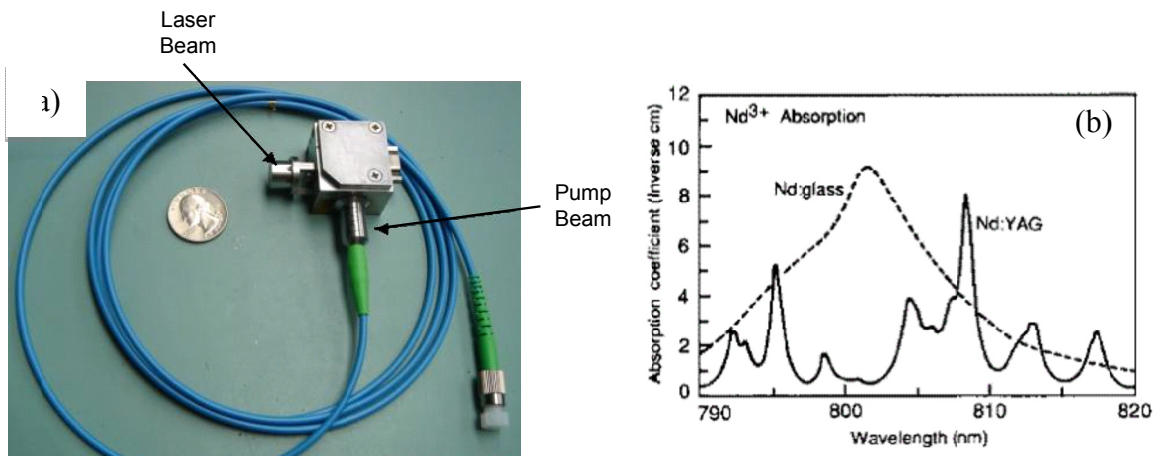


Figure 3. (a) Picture of SIM Lite NPRO based LH. The optical pump is delivered to the NPRO via multimode optical fiber. The laser beam is free space coupled to the remainder of the metrology system. (b) Nd:YAG absorption spectra, reproduced from Fan and Byer, "Diode Laser-Pumped Solid-State Lasers," IEEE Jour. Quant. Elect.7, © 1988 IEEE, with permission.

An approach along these lines was reported by Heine et al¹¹. In the reported work 4 multimode pumps, each supplying ~1W, were combined to pump a 1064nm NPRO. The drawback of unstabilized multimode pump diodes is that their lasing

spectrum changes with operating conditions. Typical multimode pumps will experience spectral shifts of 0.3nm/°C as diode temperature varies and 2nm/A as diode bias current is adjusted. Moreover, multimode pumps produce a broad spectrum, ~ 3nm, placing pump energy over a wide range of the Nd absorption spectrum, not just its sharp peak.

For SIM Lite, we have selected single mode 808 nm pumps stabilized with a Fiber Bragg Grating (FBG) in their output fiber pigtails, which are spliced to the input ports of a low loss, high port count fiber optic combiner. The narrow linewidth single mode laser enables placement of the pump power near peak Nd absorption, thus enhancing the pumping efficiency. Grating stabilization leads to stable pump spectra that drift by only ~0.02 nm/°C as the diode operating temperature varies. Overall, the module we will describe in the following sections supports 5+ yrs of continuous operation at 2 W of pump power at 808 nm with a reliability approaching 100%.

2.3 SIM Lite Programmatic Note

As we are writing this paper in late 2010, NASA has announced its decision to cancel SIM Lite mission. Nevertheless, we are confident that technologies developed for SIM Lite will be used in other future space missions. While the particular requirements, such as mission duration and output power, will likely be different, NPRO lasers have enduring appeal as space optical metrology sources, and so the presented work on developing ultra-reliable 808-nm pumps retains its relevance. More generally, the presented approach is broadly applicable to a variety of situations where multiple laser diodes must be used in parallel to meet very stringent reliability requirements.

3. SELECTING LASER PUMP MODULE ARCHITECTURE

3.1 Laser Diode Reliability Background

The reliability of laser diodes is described by a well-known “bathtub” curve showing the failure rate over time¹². Initially the failure rate decreases as some lasers die off due to the so-called “infant mortality,” usually caused by intrinsic semiconductor imperfections or defects introduced during fabrication. As time goes on, the failure rate stabilizes at a low level where it is dominated by the random failure of the diodes, with time-independent failure rate that is typically expressed in FIT – failures per billion device-hours. Later, the failure rate begins to rise again as diode “wear-out” becomes important. Typically, wear-out is due to gradual degradation of the devices that manifests itself as an increase in the pump diode current required to produce the same output optical power.

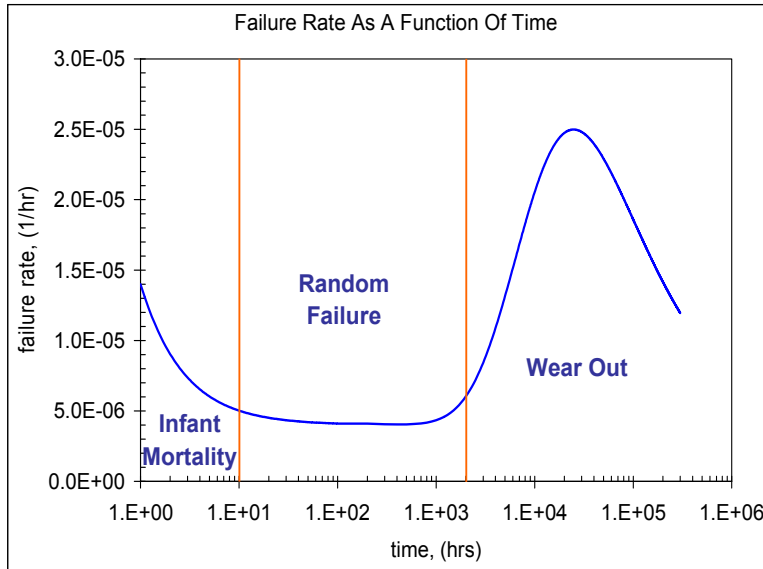


Fig. 4. Typical bathtub curve showing diode failure rate as a function of time

Laser diodes that would fail due to infant mortality are normally removed by “burn-in,” so in effect, the laser diode reliability is limited by just two factors – random failure, characterized by an exponential distribution with time-independent random failure rate λ_R , and wear-out described by a log-normal distribution, characterized by the median lifetime T_m and standard deviation σ , with failure rate¹²

$$\lambda_w(t) = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma} \frac{\exp\left(-\frac{1}{2\sigma^2} \left(\ln\left(\frac{t}{T_m}\right)\right)^2\right)}{\operatorname{erfc}\left(\frac{1}{\sqrt{2}\sigma} \ln\left(\frac{t}{T_m}\right)\right)} \quad (1)$$

Both the random failure rate and the median lifetime are affected by the operating conditions – output optical power P_{op} and temperature T_{op} , as described by the Arrhenius acceleration equations:

$$\frac{1}{\lambda_r^{op}} = \frac{1}{\lambda_r^r} \cdot \exp\left(\frac{E_{ar}}{k} \left(\frac{1}{T_{op}} - \frac{1}{T_r}\right)\right) \left(\frac{P_r}{P_{op}}\right)^{n_r} \quad (2)$$

$$T_m^{op} = T_m^r \cdot \exp\left(\frac{E_{aw}}{k} \left(\frac{1}{T_{op}} - \frac{1}{T_r}\right)\right) \left(\frac{P_r}{P_{op}}\right)^{n_w}, \quad (3)$$

where T_r and P_r are the “rated” temperature and output optical power for which the vendor measured the reported parameters λ_r^r and T_m^r , E_{ar} and E_{aw} are the random failure and wear-out activation energies, k – Boltzmann constant, n_r and n_w – power acceleration exponents for random failure and wear-out.

The output of N pump laser diodes is combined to produce the total optical pump power P_{tot} – a value that accounts for both combining and transmission losses and needs to be $\sim 2W$ in the SIM Lite metrology source. Initially, we will assume a biasing scheme where the burden of providing the required pump power is equally shared among all pump diodes still functional at a given moment, with this burden increasing some of the pumps fail with the passage of time. This approach can be described as “hot” redundancy where there is no distinction between the main and spare laser diodes. In Section 3.4 we will revisit this assumption, comparing it to alternative biasing schemes.

3.2 Monte-Carlo Numerical Simulation

To select the laser pump module architecture that will meet the SIM Lite reliability requirements, we have developed a Monte Carlo simulator incorporating the reliability concepts described above. It numerically “runs” through tens of thousands of missions, and calculates the reliability by taking the ratio of successful missions to the total number, while monitoring the convergence of calculated reliability. Each mission is subdivided into time intervals $[t, t+dt]$, that are adaptively selected so that failure probability $\lambda = \lambda_r + \lambda_w$ for every laser diode is small ($< 0.1\%$) during each interval. At every interval, random numbers are generated for all operational laser diodes that are then compared to the probability of diode failure $\lambda = \lambda_r + \lambda_w$. If the generated random number is below λ , the laser diode is considered to have failed, otherwise it survived. At the end of each interval, the number of failed lasers is tallied, and the optical power of the surviving ones is adjusted to maintain unchanged total optical output.

Arrhenius relations are then applied to calculate the new failure rates due to both wear-out and random failure for the next time interval. Since random failure mechanism has no memory, the new random failure rate depends only on the new operating conditions, and thus calculating the new λ_r from Equation 2 is straightforward. However, calculating the new λ_w is more involved, since the wear-out failure mechanism does have memory and thus depends not just on the current, but also previous laser operating conditions. We maintain the continuity of the wear-out reliability function¹³ by “time-shifting” by Δt the reliability curve corresponding to the new, increased operating power P_{op2} so that $R_w(P_{op1}, t) = R_w(P_{op2}, t - \Delta t)$ and then using failure rate $\lambda_w(P_{op2}, t - \Delta t)$. The mission is considered to have failed if the output power from each surviving laser needed to maintain a constant pump power exceeds the maximum rated power P_{max} . Maximum rated power refers to the optical power beyond which the pump diode vendor no longer warrants operation.

Based on a literature survey and discussions with vendors, we selected the simulation parameters shown in Table I. Conservatism was our guiding principle in the selection process and thus we dropped values that were outliers compared to their peers or that were derived from insufficiently rigorous testing.

Table I. Matrix of simulation parameters, including diode parameters at rated conditions, pump power requirements, and mission lifetime requirements. Rated pump power refers to the optical power specified at rated conditions (typically at room temperature).

Parameter	Value	Units
Mission Parameters		
Mission Lifetime	5.5	yrs
Mission Lifetime	48213	hrs
Reliability At Mission End	99.7	%
Optical Power Requirements		
NPRO Power	300	mW
Pump Power	1.9	W
Pump Diode Parameters		
Rated Temperature	298	K
Rated Pump Power	100	mW
Maximum Rated Power	150	mW
Diode Median Life	1.50E+04	hrs
Distribution Std Dev	1	
Wear-out Activation Energy	0.45	eV
Wear-out Power Exponent	1.1	
Random Failure Rate	2000	FIT
Random Failure Activation Energy	0.35	eV
Random Failure Power Exponent	1.1	
Pump Beam Combiner Parameters		
Coupling Coef. Per Channel	80	%

Values of random failure and wear-out power exponent, n_r and n_w , deserve a separate mention. The vendors typically report values between 2 and 5. Given this wide range of possible values, we aim to find a solution that ensures meeting mission reliability requirements for all realistic values of n .

3.3 Simulation Results – Selecting the Number of Diodes and Operating Temperature

After a trade study involving various considerations discussed below, we selected an LPM configuration with 37 laser diodes operating at -1°C.

Table II shows the minimum number of diodes required to ensure laser reliability in excess of 99.7% at mission end as a function of diode operating temperature. These results were used to bound the solution space. As temperature increases by 24°C, the number of diodes nearly doubles from 21 to 37, and the smaller number of diodes at the lowest temperature may appear more attractive. However, the colder case would require greater spacecraft thermal radiator footprint for heat dissipation. Also, it is more difficult (and expensive) for the vendors to develop and build grating-stabilized lasers designed to work at -25°C. Let us briefly consider the factors that determine the diode's lasing spectra in the context of its operating temperature. As described in the introduction and shown in figure 3(b), the desired pump wavelength is ~808nm, designed to overlap with the Nd peak absorption. For the grating stabilized single-mode pump diode the lasing wavelength is determined by the FBG bandgap. However, this applies only if the spectral separation between the gain profile and the grating bandgap is small enough. When the separation is too large, the grating can no longer provide effective feedback to the gain medium and the laser will cease operation. Given the large difference in thermal tuning coefficients between the gain profile, 0.3nm/°C, and the grating bandgap, 0.02nm/°C, it can be seen that lasers designed to operate at 25°C will not operate at -1°C, requiring custom made pump diodes lasing at 808nm at -1°C. At the same time, laser diode vendors indicated that the changes to the design and fabrication process necessary to achieve operation at -25°C are much more significant than those necessary to enable operation at -1°C.

Table II. Minimum number of diodes required as a function of diode operating temperature.

Operating Temperature, °C	Min number of pump diodes required to achieve mission reliability > 99.7%
-25	21
-20	23
-15	25
-10	28
-5	32
-1	37

There is another, more subtle reason that makes warmer operation more desirable. Of all the parameters in our device lifetime models, the power exponent n is the one we have the least confidence in, so robustness to its variation is desirable. Figure 5 shows mission reliability as a function of n for two operating temperatures, -25°C (a) and -1°C (b). The value of power exponent used to generate Table 2, $n_r = n_w = 1.1$, is very conservative for the -1°C solution but is in fact unrealistically optimistic for the -25°C solution. This follows from the fact that in the cold case, pump diodes at the beginning of life (BOL) already operate above the rated optical power: $P_{op}(t=0) = \frac{1.9}{0.8 \cdot 21} = 113mW$ and thus benefit from a smaller value of n . In contrast, the solution at -1°C has lasers that start operating at highly derated optical power $P_{op}(t=0) = \frac{1.9}{0.8 \cdot 37} = 64mW$ and continue derated operation through most of the mission, thus its probability of success increases with increasing n . For the -25°C case, a conservative value of power exponent is $n_r = n_w = 7$, and in this case the minimum number of lasers to meet requirements rises from 21 to 26.

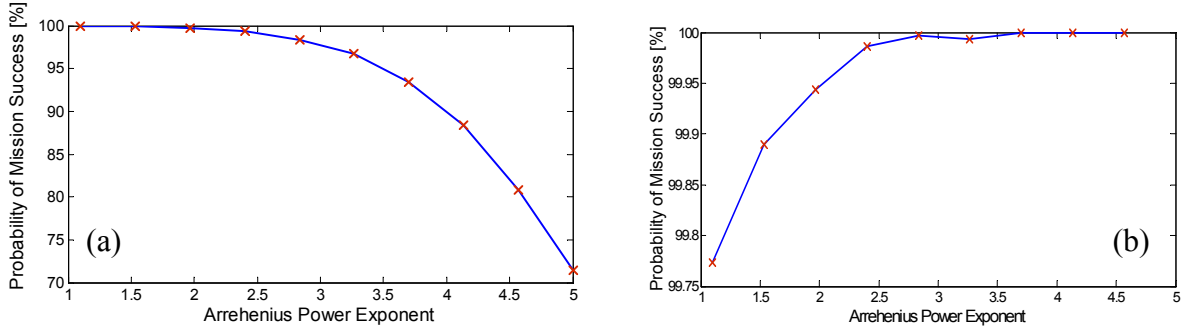


Figure 5. Plots of mission reliability as a function of n . a) -25°C and b) -1°C. Note difference in vertical scale between a) and b).

The aforementioned considerations point toward the desirability of the -1°C, 37 laser solution, as long as the outputs of 37 lasers can be efficiently combined. To this end, we have procured and tested a 37x1 all-fiber combiner with <0.5 dB insertion loss for each port. This fiber combiner was packaged and successfully passed thermal vacuum and vibration flight qualification tests. In fact, the number of input ports of this combiner was the reason we capped the maximum number of lasers for the pump module at 37.

3.4 Instantaneous Laser Farm Aging -- Selecting Optimal Bias Approach

So far we have considered just one possible biasing scheme – to equally share the burden of providing the required pump power among all laser diodes that are still alive at a given time, with this burden increasing as time goes on and some of the pumps fail. Part of the attractiveness of this approach is simplified electronics, as all diodes need to be biased in an identical fashion, another is avoiding the hazard associated with turning the lasers on and off. This approach can be described as “hot” redundancy where there is no distinction between the main and spare laser diodes.

This approach maximizes derating of the output power, thus the benefits of this approach increase with the increasing values of Arrhenius power exponents n_r and n_w . The drawback of this load-sharing approach is that by running all lasers all the time, we are always aging all of them. A diametrically opposite strategy would be a “cold” redundancy scheme where we run the minimum possible number of lasers $N = \text{ceil}(P_{\text{total}} / P_{\text{max}})$, while letting the other diodes “rest,” turning them on only as working ones fail. It is intuitively clear that this approach is appealing only if the power exponent is small.

An in-between approach, whose appeal is independent of the power exponents’ value, is to run working lasers at the rated power P_r , while the spares are turned on as needed. In general, there exists an infinite number of possible biasing schemes, including various “warm” redundancies, where the spare lasers are operating with a power output lower than that of the main units, and schemes where the biasing approach is revised in the course of the mission. The attractiveness of different approaches varies depending on the values of laser diode parameters catalogued in Table I.

In order to simplify the selection of the optimal load-sharing scheme, we propose a time varying parameter called “combined laser farm aging,” that describes aging on the interval $[t, t+dt]$ summed over all of $N(t)$ lasers operational at time t :

$$A(t)dt = \sum_{n=1}^{N(t)} \{ [\lambda_{r,n} + \lambda_{w,n}(t)]dt * R_{w,n}(t) + [1 - [\lambda_{r,n} + \lambda_{w,n}(t)]dt] * [R_{w,n}(t) - R_{w,n}(t+dt)] \} \quad (4)$$

Here, the wear-out reliability function $R_w(t) = 1 - F_w(t) = \int_t^\infty f_w(\tau)d\tau$ is designated as the remaining laser diode resource that we deplete through aging. The first term inside the sum in Eq. 4 reflects the probability of each laser’s failure during the interval $[t, t+dt]$ multiplied by its remaining wear-out reliability at time t , which is treated as the effective cost of losing this laser. The second term inside the sum in Eq. 4 shows the probability of each laser surviving time interval $[t, t+dt]$ multiplied by that laser’s aging (decrease in wear-out reliability) over dt .

After some manipulation involving basic probability identities under the assumption that dt is small and thus $(\lambda_w + \lambda_r)dt \ll 1$, we get a simple form of the combined laser farm aging expression:

$$A(t) \approx \sum_{n=1}^{N(t)} \{ [\lambda_{r,n} + \lambda_{w,n}(t)] * R_{w,n}(t) + f_{w,n}(t) \} = \sum_{n=1}^{N(t)} R_{w,n}(t) * \{ \lambda_{r,n} + 2\lambda_{w,n}(t) \} \quad (5)$$

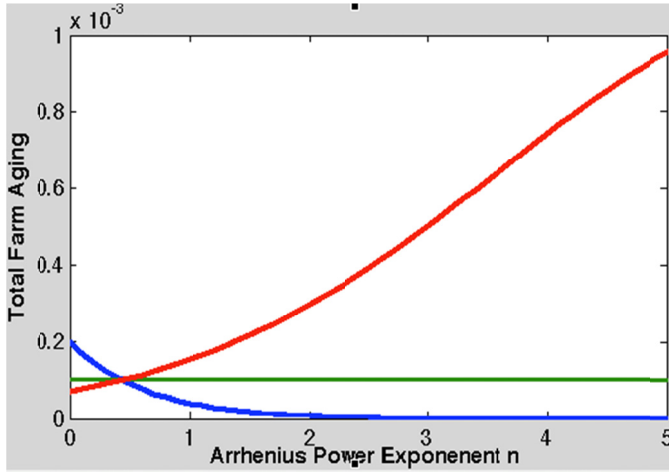


Fig. 6. Combined laser farm aging (arbitrary units) as a function of Arrhenius power exponent for hot redundancy load sharing (blue), operation at rated power (green), and operation at maximum rated power (blue).

Figure 6 shows the plot of $A(t)$, averaged over the mission duration, for three load-sharing scenarios described above as a function of Arrhenius power exponent n . Other parameters’ values used are those presented in Table I. It can be seen that

for all values of $n > 0.44$, or, in other words, all realistic values of n , the equal load sharing scenario shown in blue is preferable. Thus, the scenario we have assumed in our Monte-Carlo simulation is indeed more optimal than alternatives where redundant lasers are kept cold.

We believe that this combined laser farm aging parameter $A(t)$ is complimentary to the Monte Carlo simulations described in Section 3.2. The Monte Carlo simulations are helpful for calculating laser farm reliability for a known load-sharing approach. The additional value that parameter $A(t)$ provides is the ability to optimize, knowing previous operating conditions, the path forward. Indeed, minimizing $A(t)$ several times during the mission allows making load-sharing adjustments midcourse to reduce laser aging and increase the probability of mission success.

4. PUMP MODULE PARAMETER SENSITIVITY STUDIES

In the previous section, a laser pump module configuration that meets SIM Lite reliability requirements was selected and the load-sharing approach was chosen. It was also confirmed that this configuration remains sufficiently reliable for all realistic values of Arrhenius power exponent n , which is the parameter in whose value we have the least amount of confidence. In this section, we investigate mission reliability as a function of other parameters, some of them inherent to the particular model and batch of pump diodes and others related to the mission, in order to evaluate and, if necessary, improve the robustness of our LPM design. In all simulations, we will assume $n_r = n_w = 1.1$ – a very conservative assumption for the -1°C solution.

Figure 7(a) shows a plot of mission reliability as a function of diode (heat sink) temperature between -5°C and 5°C . It can be seen that as the temperature increases beyond the baseline value of -1°C , there is a 2°C window over which the probability of mission success exceeds 95%. Beyond this point LPM reliability decreases quickly. Based on this, we made a decision to shift the operating point of the diodes from -1°C to -5°C to become less vulnerable to unanticipated temperature fluctuations.

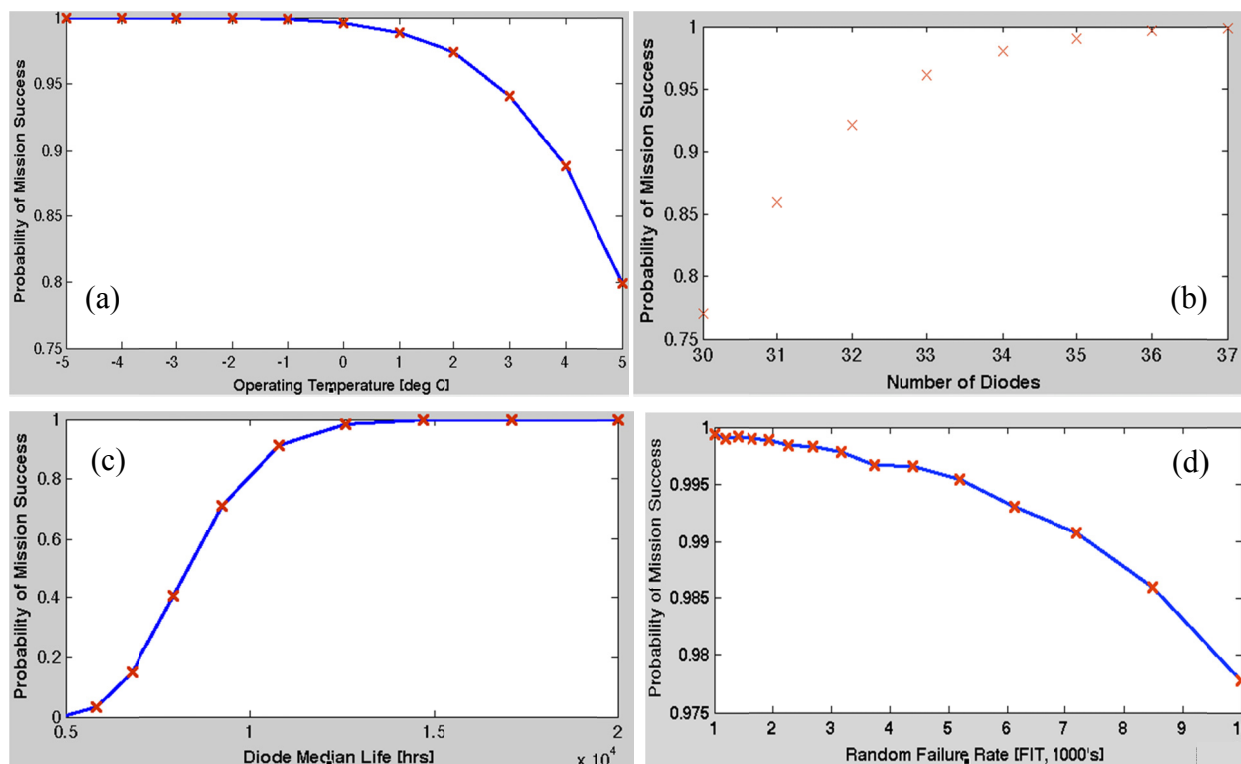


Figure 7. Sensitivity of mission success rate to a) operating temperature, b) initial number of diodes, c) diode median life at rated conditions, d) random failure rate at rated conditions.

In Figure 7(b), the effect of losing several diodes at the beginning of the mission (e.g. failure during launch) is evaluated. It can be seen that as long as there are 33 or more diodes still functional after launch, the probability of mission success still exceeds 95%; but if more diodes fail, the mission reliability falls quickly.

Figures 7(c) and 7(d) show the sensitivity of mission reliability to diode median life at rated conditions and random failure rate at rated conditions, respectively. The dramatic contrast between the two y-axis scales illustrates how wear-out is clearly the dominant failure mechanism in this situation. Mission reliability is fairly independent of random failure rate up to 4,000FIT and is only a weak function of this parameter up to 10,000FIT. On the other hand, for values of the median life shorter than 15,000hrs, the mission reliability falls off quickly. For a median life of 12,000hrs the mission reliability has already been reduced to 95% and it then collapses to near zero as the median life falls to 5,000 hours.

At BOL each of the 37 diodes operates at 170mA producing 64mW. Given maximum forward voltage of 2.4V, this translates to the total LPM electrical power consumption of 15.2W. At end of life (EOL) the likely number of diodes remaining in operation is 28 out of 37. Under this scenario each diode operates at 195mA producing 85mW, which results in a LPM power consumption of 17.3W. It is conservatively assumed here that after failure the failed diodes continue to draw electrical power in the same way as the remainder of the population.

5. CONCLUSION

In this paper we described the challenges associated with developing a metrology source laser pump module that meets SIM Lite output power and reliability requirements. Our decision to employ grating-stabilized single-mode pump diodes ensured pump wavelength stability and efficient NPRO pumping throughout the mission, but also made it necessary to use many pump lasers in parallel, with their outputs combined and delivered to the NPRO laser crystal. This configuration was made feasible by the availability of a robust and very low-loss 37x1 fiber combiner. We performed Monte-Carlo numerical simulations that allowed us to predict the reliability of a laser diode farm at various temperature and bias operating conditions. The selected solution was influenced by our desire to minimize the design's sensitivity to diode parameters with greatest uncertainty and also operate at the warmest temperature possible. We introduced a new parameter, combined laser farm aging, which allowed us to compare various load-sharing approaches. Finally, the sensitivity of the selected design to variations of different mission and device parameters was studied to evaluate, and if necessary, improve the design's robustness and consequently our confidence that the mission will be successful. After all these steps, we selected a design with 37 derated single-mode laser diodes identically biased and operating at -5°C.

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